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COLD-AIR INVESTIGATION OF A TURBINE WITH TRANSPIRATION-COOLED STATOR BLADES

III - Performance of Stator With Wire-Mesh Shell Blading

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16. Abstract

The effects on stator performance of transpiration coolant discharge from wire-mesh shell blading were experimentally determined for ratios of coolant flow to primary flow of 0 to 0.07. The results showed that transpiration coolant discharge from this type of blading caused an efficiency loss relative to comparable noncooled blading. The results for transpiration discharge from wire-mesh shell blading are similar to results previously obtained for transpiration discharge from discrete hole blading. A comparison of the effects on stator efficiency of transpiration discharge and trailing-edge discharge shows a significantly larger loss for transpiration discharge.

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SUMMARY

At the NASA Lewis Research Center, the effects on turbine performance of different means of stator-blade coolant ejection are being investigated. This report presents the results of a detailed experimental and analytical investigation of the effects on stator performance of stator-blade transpiration coolant discharge from wire-mesh shell blading. The investigation included the effects on stator mass flow and efficiency over a range of coolant mass flows from 0 to about 7 percent of primary mass flow.

Relative to the mass flow with zero coolant, the total mass flow of the subject stator remained essentially constant with varying coolant discharge. As compared to the efficiency of a comparable noncooled stator, the primary-air efficiency decreased a small amount with increased coolant rate and the thermodynamic efficiency decreased a large amount. (The primary-air efficiency relates the actual kinetic energy output to the ideal energy of the primary flow only; the thermodynamic efficiency charges the stator with the ideal energy of both the primary and coolant flows.) For example, over the range of coolant flow rates of practical interest (from about 2 to 7 percent), the decrease in primary-air efficiency was about 1 percent between 2 and 5 percent coolant flow and about 2 percent at 7 percent coolant flow. The decrease in thermodynamic efficiency was about 3 percent at 2 percent coolant flow and about 14.5 percent at 7 percent coolant flow. These results are similar to those for transpiration discharge from discrete hole shell blading. When compared with results for stator-blade trailing-edge coolant discharge, the penalty in efficiency for stator transpiration coolant discharge is large. This large penalty is caused by the difference in location and direction of coolant discharge for the two methods.

A comparison was made of predicted and experimental effects of transpiration discharge on primary-air efficiency over the coolant flow range between 2 and 7 percent. Relative to the efficiency of a noncooled blade, the predicted results showed about 0.1 to 0.4 percent gain in primary-air efficiency. The experimental results showed about a 1 to 2 percent loss in primary-air efficiency.

INTRODUCTION

To meet performance requirements, many advanced gas turbine engines must operate at high turbine inlet temperatures. In some cases, these temperatures are high enough that the turbine blading must be cooled to avoid exceeding the stress and oxidation limitations of currently available materials. The general method for cooling the blading is to bleed air from the compressor, direct it through the turbine blading for cooling, and then discharge it from the blading into the main gas stream. The means of discharging the coolant from the blading into the main gas stream are different for different cooled-blade designs. In reference 1, an analysis is presented which indicates that different means of coolant ejection affect turbine performance quite differently. To confirm these findings experimentally, an investigation is being conducted at Lewis to determine the effect on turbine blade row and stage performance of several means of coolant discharge that are typical of different cooled-blade designs.

The first coolant discharge method investigated was stator-blade trailing-edge ejection. In that investigation, the coolant was discharged into the main gas stream through a slot along the entire length of the stator-blade trailing edge. The results of the investigation, which include the effects of stator-blade trailing-edge ejection on both stator and stage performance, are reported in references 2 to 4. The results show that the flow of coolant caused only small changes in both stator and stage thermodynamic efficiencies. From the stator and stage results, it was also deduced that the rotor efficiency was not significantly affected by the flow of coolant.

An investigation of the effect of stator-blade transpiration coolant ejection on turbine stator and stage performance is now being made. With transpiration cooling, the coolant enters into hollow blades and is then ejected through a porous shell that constitutes all, or practically all, of the outer blade surface.

Two different types of transpiration stator blading are being investigated. One type has a self-supporting outer shell with discrete cooling holes and variable porosity over the blade surface. The other type has a core-supported wire-mesh outer shell and constant porosity over the blade surface.

The investigation of the stator having discrete hole blading has been completed and the effects of this type of transpiration stator-blade ejection on both stator and stage performance are reported in references 5 and 6. These results show that the discharge of coolant from this type of transpiration stator blading caused a significant loss in both stator and stage thermodynamic efficiencies.

This report presents the results of an investigation of the stator having wire-mesh shell transpiration blading. The results include the effect of this type of transpiration coolant discharge on stator mass flow and overall stator efficiency. Results for this subject stator are compared with corresponding results both for the stator having dis-

crete hole transpiration discharge and for the stator having trailing-edge discharge. In addition, the experimental effects of transpiration discharge on stator efficiency are compared with predicted effects.

During this investigation, the inlet temperatures of the primary and coolant flow were the same, so the results include no actual cooling effects. The results are for coolant flow rates from 0 to 7 percent of the primary mass flow. Mass-flow and outlet-flow-angle results were obtained for a range of stator-inlet to downstream pressure ratios. Stator efficiency results were obtained at a constant stator-inlet to downstream hub pressure ratio of 1.72, corresponding to stator design conditions.

SYMBOLS

p	pressure, psi; N/m^2
V	absolute gas velocity, ft/sec; m/sec
w	mass-flow rate, lb/sec; kg/sec
y	coolant fraction, ratio of coolant flow to primary mass flow
α	flow angle at blade outlet measured from axial direction, deg
δ	ratio of stator-inlet pressure to U. S. standard sea-level pressure
η_b	efficiency of base noncooled stator
η_p	stator primary-air efficiency (stator kinetic energy output expressed as fraction of ideal energy of primary flow only)
η_t	stator thermodynamic efficiency (stator kinetic energy output expressed as fraction of ideal energies of both primary and coolant flows)
θ_{cr}	squared ratio of critical velocity at stator inlet to critical velocity of U. S. standard sea-level air

Subscripts:

av	average of hub and tip conditions
cr	conditions at Mach 1
d	measuring station downstream of blading
h	hub
m	blade mean section
o	absence of coolant flow
0	measuring station upstream of blading

1 measuring station at stator throat

2 measuring station just downstream of stator blade trailing edge

3 station where complete mixing occurs

3d three-dimensional, or annular, sector

Superscript:

' total state

APPARATUS

The apparatus used in the investigation consisted of the test stator and an appropriate test facility. The facility, which is shown in figures 1 and 2, is the same as that described in reference 5.

In figure 3, a composite photograph of the subject blading and a magnified section of the blade surface is shown. In the magnified view the individual wires of the porous wire-mesh shell material are evident.

The parts and method of blade construction are shown in figure 4. Figure 4(a) is the core which is used as the structural support for the 0.025-inch (0.64-mm) thick wire-mesh shell which is depicted in figure 4(b). In figure 4(c) the various welding operations required to obtain the desired profile have been completed. The assembled blade is shown in figure 4(d) with the end cap installed.

During fabrication, deviations from the desired blade profile as specified in reference 7 occur. One deviation is the valleys formed by the compactions at the electron-beam weldments. Another deviation is the variation from desired surface curvature caused by unavoidable stretching of the porous shell material between the core ribs.

In figure 5, the subject blading is compared with other blading previously investigated having different coolant provisions. The blading in figure 5(a) is for trailing-edge discharge and that in figure 5(b) is for discrete hole coolant discharge.

The profile and primary-air flow path of the three bladings in figure 5 are the same, within manufacturing tolerances, as those described in reference 7. There are 50 blades in the stator. The tip diameter is 30.0 inches (76.20 cm) and the blade height is 4.0 inches (10.16 cm). Each blade has a 2.26-inch (5.74-cm) mean radius chord. Design exit angle at the mean section is 67°.

INSTRUMENTATION

The instrumentation required for obtaining the reported results is the same as that described in reference 5. Briefly, a Dall-tube flowmeter was used to measure the

primary-air flow rate, and a venturi meter was used to measure the coolant flow rate. In the stator test section, total and static pressures were measured at the locations shown in figures 6 and 7. Inlet total pressures were measured with Kiel-type total-pressure probes; downstream total pressures were measured with a total-pressure survey probe of the modified type described in detail in reference 8; and static pressures were measured using conventional static-pressure taps.

TEST AND CALCULATION PROCEDURES

The fluid used in the investigation for both the primary and coolant flow was laboratory combustion air at a total temperature of about 545° R (303 K). The stator-inlet pressure of the primary air was 30.0 inches of mercury absolute (10.16 N/cm^2).

Mass flow characteristics and outlet flow angle data were obtained for a desired range of overall stator pressure ratios $p_0'/p_{d,h}$ and coolant flow rates. Pressure ratios were set by holding the upstream pressure constant and adjusting the downstream pressure. At each pressure ratio setting, the coolant mass-flow rate was varied by regulating the inlet pressure of the coolant. The stator-outlet flow angles were measured by traversing radially across the blade span with the probe situated midway between wakes. When the flow angles were measured, the probe was located about 0.5 inch (1.27 cm) axially downstream of the stator-blade trailing edge.

Stator pressure-loss data were obtained at a constant overall stator-hub pressure ratio of 1.72, corresponding to design conditions for the stator of reference 7, and with nominal coolant flow rates of 0, 2, 4.5, and 7 percent of the primary flow. At each coolant flow rate, annular surveys of total-pressure loss were made for approximately 1 blade pitch (fig. 7) with the probe sensing element located approximately 0.23 inch (0.57 cm) axially downstream of the trailing edge. These annular surveys were made by conducting circumferential surveys at a sufficient number of different radii to adequately define the loss for the complete annular sector. These data were used to determine the stator efficiencies.

The test and calculation procedures used in determining the stator mass-flow results were those conventionally used for venturi and Dall-tube-type flowmeters. Efficiency results were computed using the procedures summarized in reference 3, and the predicted effect of transpiration discharge was computed as described in reference 5.

RESULTS AND DISCUSSION

The investigation of the effects on stator performance of transpiration discharge of coolant through core-supported wire-mesh shell blading was made for nominal coolant

flow rates of 0, 2, 4.5, and 7 percent of the primary flow. Mass-flow and outlet-flow-angle results were obtained for a range of stator-inlet total-pressure to downstream static-pressure ratios. Efficiency results were obtained at a constant stator-inlet total-pressure to downstream hub static-pressure ratio of 1.72, which corresponded to stator design conditions (ref. 7). This hub pressure ratio of 1.72 is equivalent to an average hub-tip pressure ratio of 1.55.

For the subject investigation, the minimum transpiration coolant flow rate presented in the results is approximately 2 percent of the primary flow. This coolant flow rate occurs when the coolant pressure inside the blading is slightly higher (≈1 in. of Hg or 0.34 N/cm^2) than the highest pressure on the blade surface (inlet stagnation pressure). Values of coolant pressure lower than stator primary-air inlet stagnation pressure with corresponding lower coolant rates represent unrealistic operating conditions since some of the primary air flows abnormally through the wire-mesh skin into the core spaces of the blading.

To determine the effects of coolant discharge on the performance of a stator requires that the base-noncooled-stator performance be established. The blading chosen for the base-noncooled-stator performance was that having discrete coolant holes with the coolant holes sealed (ref. 5). The shape and primary flow path of this blading were the same as those of the subject blading without the surface deviations caused by the wire-mesh construction.

The results are presented in four sections. The first section presents the experimental results for the subject stator. The second section compares the experimental results for the subject stator with similar results for the stator of reference 5 having blading with discrete hole transpiration coolant ejection. The third section compares the experimental results for the stators having transpiration coolant ejection with the stator of reference 3 having blading with trailing-edge coolant ejection. In the last section, the experimentally determined results for the subject stator are compared with those predicted analytically.

Experimental Performance of Stator with Wire-Mesh Blading

The first part of this section concerns mass-flow characteristics and the last part relates to stator efficiency.

Mass flow. - In figure 8 the equivalent primary-air mass flow is shown as a function of the ratio of stator-inlet total pressure to average downstream static pressure $p_0'/p_{d,av}$ and as a function of coolant flow. The curves shown were obtained from crossplots of experimental data.

Decreasing primary flow with increasing coolant flow is evident at all pressure ratios. Examination of the data shows that, for a given pressure ratio, the decrease in

primary flow with coolant addition is about equal to the increase in coolant flow. The total flow then remains about constant. The variation in total flow is shown in figure 9 for the design pressure ratio.

The constant total flow with increasing coolant flow shown in figure 9 may be explained as follows: At the stator throat, the average coolant velocity is less than the average primary-air velocity. This is so because the total pressure of the coolant in the direction of primary flow at the point of discharge on the blade surface is less than the total pressure of the primary flow. As the coolant flow rate is increased, the coolant flow fills an increased portion of the throat area. The total flow therefore would be expected to decrease. However, figure 9 shows that the total flow remains constant. Since the total flow is constant, it must be concluded that the decrease in throat flow with increased coolant flow is compensated by an increase in coolant flow through the suction surface of the blading downstream of the throat.

A consideration not shown in the results of figure 9 is that the mass flow with zero coolant represents a loss in mass flow relative to solid blading. This loss in mass flow with wire-mesh shell blading is caused by part of the flow circulating through the shell into and out of the core spaces instead of expanding along smooth boundary surfaces as it would in solid blading. An example of the loss in stator flow resulting from having transpiration blading holes open was reported in reference 5 for the stator with discrete hole blading. For this reference blading, the loss in stator flow with the holes open was about 1.5 percent of the flow with the holes closed. Some flow loss would also be expected for the subject stator.

Flow angle. - The stator outlet flow angles α_2 obtained at the design pressure ratio with various coolant fractions are shown in figure 10. (The data points shown were obtained from curves faired through average experimental free-stream traces. Outlet flow angles for other pressure ratios showed little deviation from the data shown in figure 10 and consequently are not shown.) The outlet flow angles are, on the average, little affected by coolant addition. The outlet-flow-angle results are, then, consistent with the mass-flow results reported previously which showed the total flow to remain constant with coolant addition.

Although the average outlet flow angles in figure 10 are about the same, small radial variations with coolant flow are evidenced, there being some underturning at the hub and some overturning at the tip with increased coolant flow. These radial variations in outlet flow angle could have been caused by radial pressure gradients or by a secondary flow phenomenon or by more coolant being ejected in the hub region than in the tip region.

Efficiency. - These results are presented in terms of both a primary-air efficiency η_p and a thermodynamic efficiency η_t. (The primary-air efficiency relates the actual kinetic energy of the primary and coolant flows to the ideal kinetic energy of the primary

flow only, while the thermodynamic efficiency relates the same actual kinetic energy of the combined flows to the sum of both the primary- and coolant-flow ideal energies.) Values of thermodynamic efficiency presented are based on charging the coolant flow with the ideal energy between the coolant supply annulus (see fig. 6) and stator-exit static pressure. The data shown were taken near design stator pressure ratio.

In figure 11, the variation of annular-sector, after-mix, primary-air efficiency with transpiration coolant flow rate is presented. Relative to the efficiency of the base noncooled stator, the figure shows a loss in primary-air efficiency of about 1 percent between about 2 and 5 percent coolant flow rates. This loss increases to about 2 percent at 7 percent coolant flow. These results indicate that any increase in output resulting from the flow of coolant is more than offset by a decrease in output due to the coolant flow mixing and interfering with the primary flow. Possible reasons for this occurrence are discussed in the following two paragraphs.

With transpiration cooling, the direction of the coolant at the point of discharge is generally perpendicular to the direction of the main gas stream. Therefore, at the point of injection, the coolant flow, having a nominally zero component of velocity in the direction of the main gas stream, contributes little, if any, useful energy to the flow. After being injected into the main gas stream, the coolant possesses ideal available energy corresponding to the static head between the point of discharge and the blade exit. However, on the suction surface of the blading, in the area of diffusion, this static head is not positive, but negative, since the static pressure at the point of discharge is less than the static pressure at the blade exit. For blading with this geometry, the diffusion area represents a considerable portion of the total blade surface, as shown in figure 13 of reference 7. To discharge flow perpendicular to the main gas stream, at low velocity, in a negative pressure gradient would seem to contribute to a thickening (and possibly separation) of the boundary layer of the main gas stream. It is also possible that the ejection of the coolant increases the friction loss of the primary flow, since the coolant flow might act as an irregular surface.

For a part of the coolant discharged from the blade surface, there is positive static head between the point of coolant discharge and the blade exit. This static head is converted, at some efficiency, into kinetic energy that contributes to the useful output of the blade row. However, as discussed in the previous section (Mass flow), the velocity of all portions of the coolant flow is less after expansion than the velocity of the primary flow. As a result, some of the useful output of the blade row is lost because of the coolant flow mixing with the primary flow.

Summarizing, the net result of the effects discussed in the preceding two paragraphs is that any increase in output resulting from the expansion of the coolant is more than offset by a reduction in output caused by the coolant flow mixing and interfering with the main gas stream.

In figure 12 experimentally determined values of annular-sector, after-mix, thermodynamic efficiency η_t are shown as a function of coolant rate. The thermodynamic efficiency decreases sharply with coolant flow rate. For instance, the efficiency of the base noncooled blading is 97.5 percent. At about 2 percent coolant flow, the efficiency is about 94.5 percent and at about 7 percent coolant flow, the efficiency is about 82.5 percent; these represent decreases of about 3.0 and 14.5 percent, respectively, relative to the efficiency of the base noncooled blading. The much larger decrease in thermodynamic efficiency (fig. 12) compared to the decrease in primary-air efficiency (fig. 11) results, of course, from the fact that the thermodynamic efficiency is charged with the coolant-flow ideal energy.

Comparison of Experimental Performance of Stators with Wire-Mesh Shell and Discrete Hole Shell Blading

The first part of this section compares the effects of the two transpiration discharge methods on stator mass flow and the last part compares the effects on overall efficiency. The data presented are near design stator pressure ratio.

Since discharge of coolant through wire-mesh or discrete hole shell blading are merely variations of the general method of transpiration coolant discharge, the effects on stator performance of coolant discharge from the two types of blading would be expected to be similar.

Mass flow. - In figure 8 of reference 5 the fractional variation in total mass flow as a function of coolant flow for the discrete hole blading is presented. Relative to the mass flow with the coolant holes sealed this variation was zero, which agrees with the results presented in figure 9 for the subject wire-mesh stator. Although the overall effects on stator mass flow of coolant discharge from wire-mesh shell and discrete hole shell blading are the same, different radial variations in pressure-loss patterns did occur. Possible implications of these differences are worth noting.

The pressure-loss data for the two types of blade walls are compared in figure 13. The data presented are for zero and 7 percent coolant at three radial locations: 3.5, 2 (mean section), and 0.5 inches (8.9, 5.08, and 1.27 cm) from the blade hub. The data shown near the hub and tip are far enough from the end walls to exclude end-wall loss. With zero coolant flow, the data show about the same radial variation in pressure-loss patterns for the two types of shell. This is different than with 7 percent coolant flow, where the data show that the stator having wire-mesh shell blading had a large radial variation in loss pattern, with the largest loss being near the hub. The stator having discrete hole shell blading had practically no radial variation in loss patterns.

These differences in loss patterns are shown since they affect the radial variation in mass flow. Knowing the variation, it might be desirable when designing a stator to adjust the stator area to compensate for the variation.

It is noted that the variations in pressure loss patterns are reflected in the stator-outlet flow-angle data. In figure 10, although the mean-section outlet flow angle is shown to remain constant with increased coolant flow, the angle near the hub decreased and the angle near the tip increased. The same type of data for the discrete hole blading presented in figure 9 of reference 5 shows little, if any, radial variation in outlet flow angle with increased coolant flow.

The large difference in radial variation in the loss patterns for the two types of blade shells may result from differences in radial variations in coolant flow rate and/or differences in the discharge velocity of the coolant. With wire-mesh shell blading, radial variations might occur because of 10 different-size chambers or core spaces (see fig. 4(c)) supplying coolant. In addition, the coolant is introduced into the individual core spaces through metering orifices (see fig. 4(d)) located in the blade end caps. The metering orifices in the wire-mesh shell blading would be expected to cause high internal coolant velocities in the cavities adjacent to the inner surface of the wire-mesh shell blading. This could cause radial variations in internal static pressure. This possible variation in internal static pressure of the wire-mesh shell blading would cause large radial variations in coolant flow. The variation in coolant flow, because of its low momentum, would be evidenced as radial variations in loss patterns. The discrete hole blading has only one large cavity to feed the coolant to the porous shell. This large inlet area and internal volume acts as a plenum chamber to supply the coolant at an essentially uniform static pressure to the inner surface of the discrete hole blade.

The differences in radial variations in loss patterns for the two types of shells might also be caused by differences in coolant discharge velocity. With wire-mesh shell blading, the coolant flow area is more evenly distributed over the blade surface than with discrete hole blading. The coolant is then discharged somewhat as a blanket at a lower velocity than with discrete hole blading, where the coolant is discharged as low-velocity jets. As a result, the coolant from the wire-mesh shell blading, because of its lower discharge velocity, may follow the secondary flow path of the stator more readily than does the coolant from the discrete hole blading. With wire-mesh shell blading, there would then be larger flow of low-momentum coolant fluid toward the hub region than with discrete hole blading. This would also be evidenced by a larger radial variation in loss patterns.

Efficiency. - Figure 14 compares the effects on stator primary-air efficiency of the two types of transpiration discharge. The results for the two variations in transpiration discharge are similar in both magnitude and trend. The small differences between the results are believed to be caused by differences in coolant pressure drop and/or in coolant ejection velocity of the two types of blade shells.

In figure 15, the effects on stator thermodynamic efficiency of the two types of transpiration discharge are compared. In the practical range of coolant rates, the trend of decrease in thermodynamic efficiency with increased coolant flow is greater for the stator with wire-mesh blading than for the stator with discrete hole blading. This occurs principally because of differences in coolant pressure drop for the two tested bladings. At the same coolant flow, the pressure drop for the wire-mesh blading is greater than that for the discrete hole blading. This is indicated by the fact that, when the coolant inlet pressure is about 1 inch of mercury ($0.34\ N/cm^2$) above the primary-air inlet pressure, the stator with wire-mesh shell blading has approximately 2 percent coolant flow, while the stator with discrete hole shell blading has about 3.25 percent coolant flow. Because of this difference in coolant pressure drop at the same coolant rate, the stator with wire-mesh blading is charged with more ideal coolant energy than the stator with discrete hole blading. Consequently, at the same coolant rate, the difference between primary-air efficiency and thermodynamic efficiency for the stator with wire-mesh shell blading is greater than that for the stator with discrete hole shell blading. If the coolant pressure drop of the two stators with different types of transpiration blading were the same, the difference in thermodynamic efficiency between the two stators would be expected to be about the same small difference as shown for primary-air efficiency in figure 14.

Comparison of Experimental Performance of Stators with Transpiration Discharge and Trailing-Edge Discharge

The results of this section are presented in two parts. The first part compares the effects on stator mass flow of coolant discharge from wire-mesh shell and discrete hole shell blading with the effects on stator mass flow of coolant discharge from blading with a trailing-edge slot. In the second part, the effects on stator efficiency of the two coolant discharge methods are compared.

Mass flow. - Figure 16 presents the fractional variation in total mass flow for the two discharge methods as a function of coolant rate. As previously discussed, with transpiration ejection, the total flow remains about constant with the addition of coolant when compared to the flow with zero coolant with the holes open. With trailing-edge discharge of coolant, there is a large increase in total flow with increased coolant addition.

The principal reason for the different trends in total mass flow of the two methods of discharge is the different coolant discharge locations. With transpiration discharge of coolant, most of the coolant is discharged upstream of the stator throat. The coolant then fills part of the available throat area so that the primary flow is reduced. With trailing-edge ejection, the coolant is discharged downstream of the throat. The throat

area does not have to accommodate the coolant flow, and the primary flow remains nearly constant.

Efficiency. - In figure 17 a comparison is presented of the fractional change in primary-air efficiency as a function of coolant flow for both transpiration discharge and trailing-edge discharge of coolant. As with mass-flow characteristics, the results are quite different for the two types of coolant discharge. With trailing-edge discharge, the primary-air efficiency increases with increasing coolant flow (ref. 3). Both transpiration-type stators yielded lower and relatively flat efficiency trends with coolant-flow addition. This difference in trends is caused primarily by the differences in the location and direction of coolant ejection for the two types of discharge. With transpiration coolant discharge, the coolant is ejected generally perpendicular to the main flow and so contributes little, if any, useful kinetic energy at the point of discharge. An increase in kinetic energy can result because of the expansion of the coolant flow from the point of discharge. However, whatever portion of this output is realized, it is more than offset by a reduction in output resulting from the coolant flow entering normal to, and mixing with, the main gas stream. The result is a net decrease in primary-air efficiency.

With trailing-edge ejection, the coolant is discharged at the downstream stagnation point of the blading and in the direction of primary flow. Since it is discharged at this location, the coolant flow has no apparent effect on the flow of the primary fluid; and, since it is discharged in the direction of flow, it contributes its kinetic energy to the useful output of the primary fluid. In addition, as explained in reference 3, there is a reduction in trailing-edge loss with trailing-edge ejection, which increases the specific output. For these reasons, the primary-air efficiency with trailing-edge ejection continually increases as the coolant rate increases.

Summarizing, the results in figure 17 indicate that, with transpiration discharge, the coolant flow contributes little, if any, useful output to the stator-blade row and has an adverse effect on the efficiency of the primary flow. With trailing-edge discharge, the coolant flow contributes to the useful output of the stator and apparently has little, if any, effect on the efficiency of the primary flow.

In figure 18, the effect on stator thermodynamic efficiency of transpiration and trailing-edge coolant discharge is compared. With transpiration discharge, the thermodynamic efficiency decreases rapidly with increased coolant flow. With trailing-edge ejection, the thermodynamic efficiency first increases and then decreases, with the total variation being about 2 percent.

Comparing the trend of thermodynamic efficiency in figure 18 with that of primary-air efficiency in figure 17 for either of the two discharge methods reveals that the trend of thermodynamic efficiency falls below the trend of primary-air efficiency and by an increasing amount with increased coolant flow. This occurs, of course, because the

thermodynamic efficiency is charged with increasing amounts of coolant-flow ideal energy as the coolant flow is increased, and the primary-air efficiency is not. The reasons for the trends in thermodynamic efficiency are then the same as the reasons for the trends in primary-air efficiency except that the thermodynamic efficiency is charged with the coolant-flow ideal energy.

Comparison of Experimental and Predicted Stator Efficiencies

In reference 5, an analytical method for predicting the effect on stator efficiency of transpiration coolant discharge was described. In figure 19, the fractional variation in primary-air efficiency for the subject stator, predicted by using the described analytical method, is compared with the experimentally determined variation. In the range of coolant flows of interest, between 2 and 7 percent, the predicted results show about 0.1 to 0.4 percent gain in primary-air efficiency; whereas the experimental results show about 1 to 2 percent loss in primary-air efficiency. The predicted results indicate that the coolant flow contributes nearly zero output to the blade row. The discrepancy between predicted and experimental results is apparently due to the fact that the prediction method assumes that the flow of coolant has no effect on the efficiency of the primary flow, while the experimental results show that the coolant flow adversely affects the efficiency of the primary flow.

SUMMARY OF RESULTS

An investigation was made to determine the effects on turbine stator performance of transpiration coolant ejection through a constant-porosity, wire-mesh shell, core-supported blade wall. The effects of this type of transpiration coolant discharge on stator mass flow, outlet flow angle, and efficiency were obtained for coolant flow rates from zero to 7 percent of primary mass flow. The effects on stator mass-flow characteristics and outlet flow angles were investigated for a range of stator-inlet total-pressure to downstream static-pressure ratios, while the effects on stator efficiency were investigated at a constant stator-inlet total-pressure to hub downstream static-pressure ratio of 1.72. Results are compared to those obtained for the discrete hole transpiration-cooled blade and the trailing-edge-ejection-cooled blade.

For this blading, the operation between 0 and 2 percent coolant flow is impractical. Under these conditions the upstream part of the wire-mesh shell blade passes no coolant, with some of the primary air flowing abnormally through the wire-mesh shell into the core spaces.

The results for the subject stator are as follows:

1. With coolant flow rates between about 2 and 7 percent, the total mass flow was essentially constant relative to the mass flow with zero coolant flow, with the wire-mesh skin open. This finding apparently results from the fact, that, as the coolant flow rate is increased, the decrease in mass flow at the stator throat is compensated by an increase in coolant flow downstream of the throat on the suction surface of the blading.

2. With changing coolant rate, the average outlet flow angle of the subject stator was about constant, with small variations from blade hub to blade tip. Pressure-loss data indicated the small variations in flow angle to be caused either by radial variations in coolant flow rate with changing coolant flows or by a secondary flow phenomenon in which the low-momentum coolant flow accumulates at the hub region in increased amounts with increased coolant flow.

3. Between about 2 and 5 percent coolant flow, the primary-air efficiency of the subject stator was about 1 percent less than the efficiency of the base noncooled stator. At 7 percent coolant flow, the primary-air efficiency decreased to a value which was about 2 percent less than the efficiency of the base noncooled stator. These results indicate that any increase in kinetic energy output attributable to the expansion of the coolant flow is more than offset by a decrease in output due to the coolant flow mixing and interfering with the primary flow.

4. The thermodynamic efficiency of the subject stator continually decreased with increased coolant flow. For instance, relative to the efficiency of the base noncooled stator, the decrease was about 3 percent at 2 percent coolant flow and about 14.5 percent at about 7 percent coolant flow. The larger loss in thermodynamic efficiency than in primary-air efficiency, relative to the efficiency of the base noncooled stator, results from the fact that the thermodynamic efficiency is charged with the coolant-flow ideal energy and the primary-air efficiency is not.

5. A comparison of the effects on stator performance of transpiration coolant discharge from wire-mesh and discrete hole shell blading showed that the effects on performance of discharge from the two types of blade shell are similar. Some differences are shown between the results for the two types of blading, but the evidence indicates that these differences are caused, for the most part, by differences in coolant pressure drop.

6. A comparison of the effects on stator performance of transpiration and trailing-edge coolant discharge show that transpiration discharge causes a significantly larger loss in performance than trailing-edge discharge. The major reasons for the different effects of the two methods are thought to be the different locations and direction of coolant discharge of the two methods.

7. A comparison was made of predicted and experimental effects of transpiration discharge on primary-air efficiency over the coolant flow range between 2 and 7 percent.

Relative to the efficiency of a base noncooled blade, the predicted results showed about a 0.1 to 0.4 percent gain in primary-air efficiency. The experimental results showed about a 1 to 2 percent loss in primary-air efficiency.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 4, 1970,
720-03.

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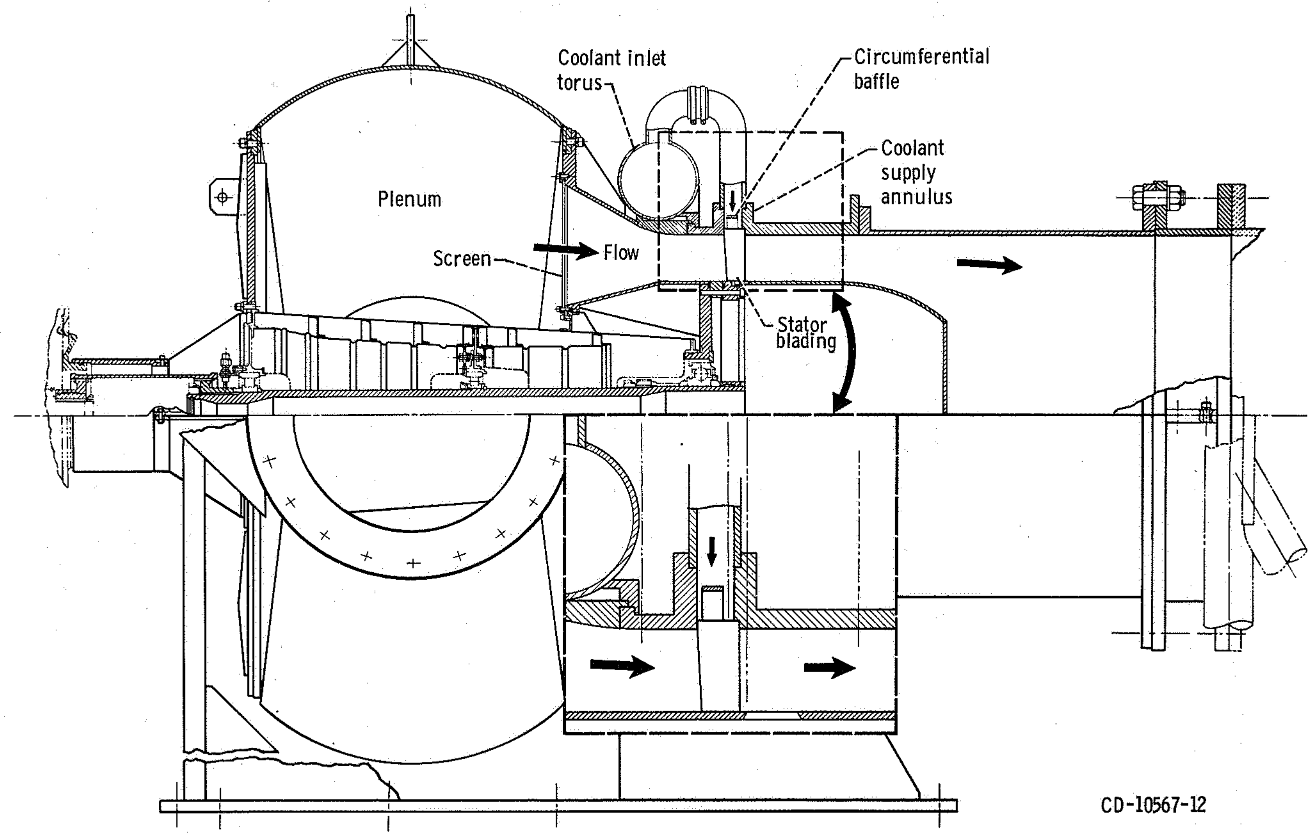


Figure 1. - Cross section of test facility.

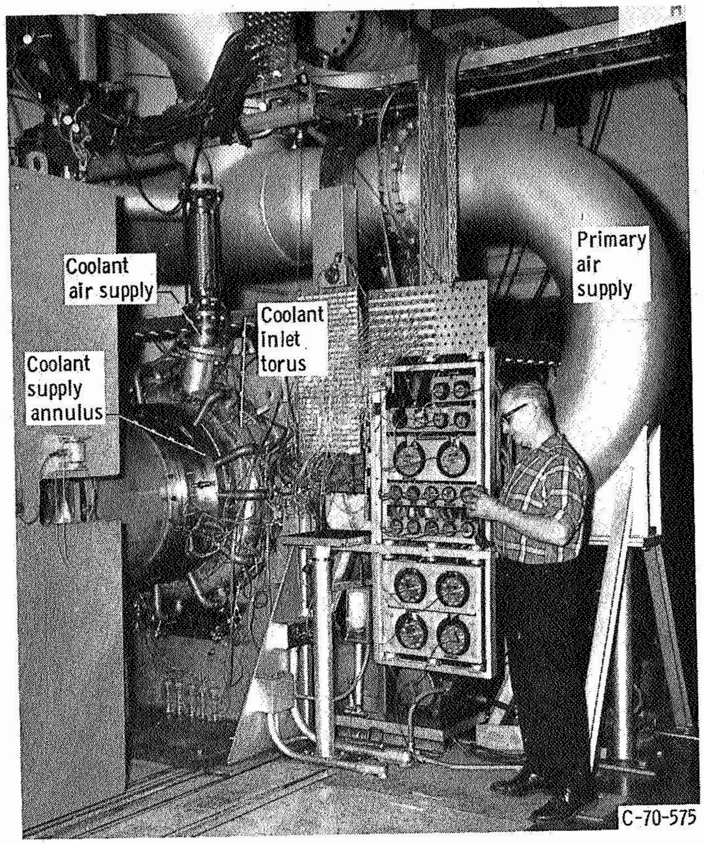
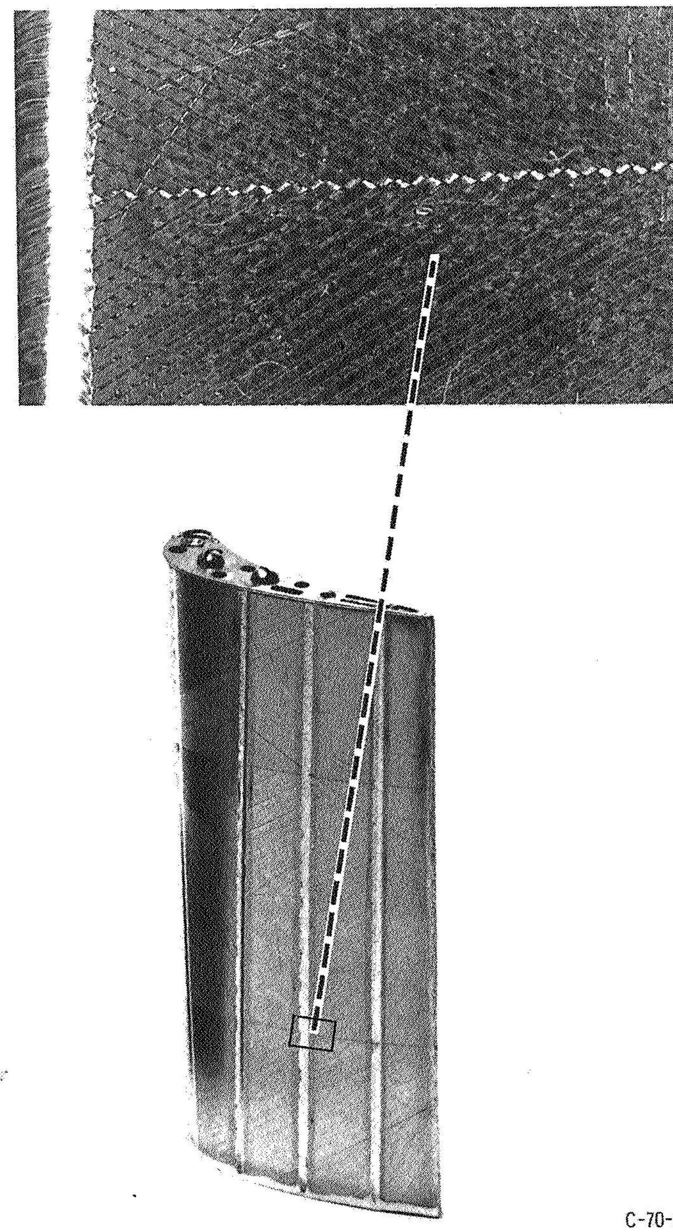
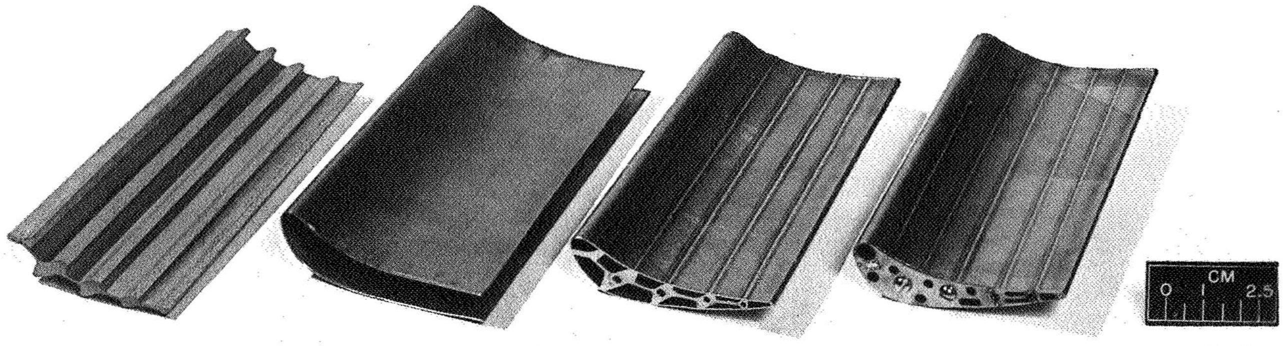


Figure 2. - Test facility.



C-70-551

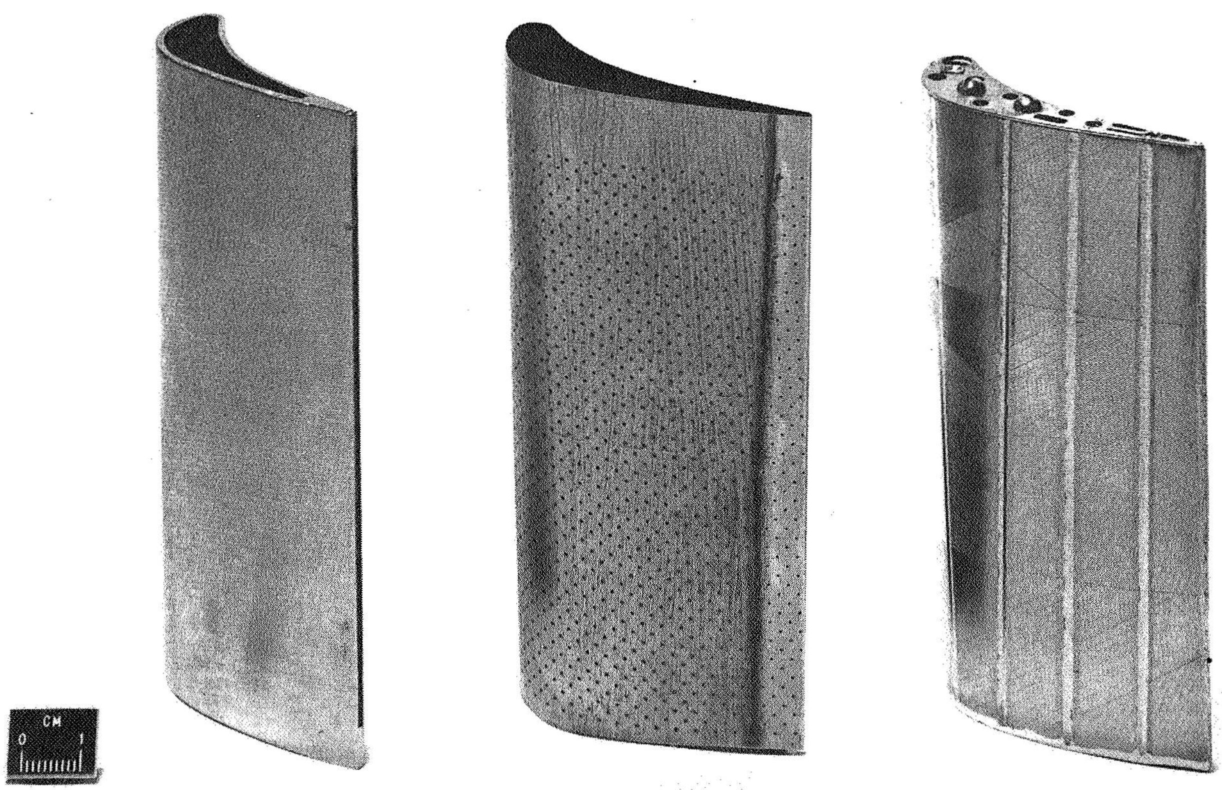
Figure 3. - Wire-mesh shell blade and magnification of shell material.



C-70-238

(a) Core. (b) Shell. (c) Welded blade. (d) Assembled blade.

Figure 4. - Wire-mesh shell blade parts and assembly.



C-70-447

(a) Trailing-edge slot. (b) Discrete hole shell. (c) Wire-mesh shell.

Figure 5. - Comparison of bladings with different cooling provisions.

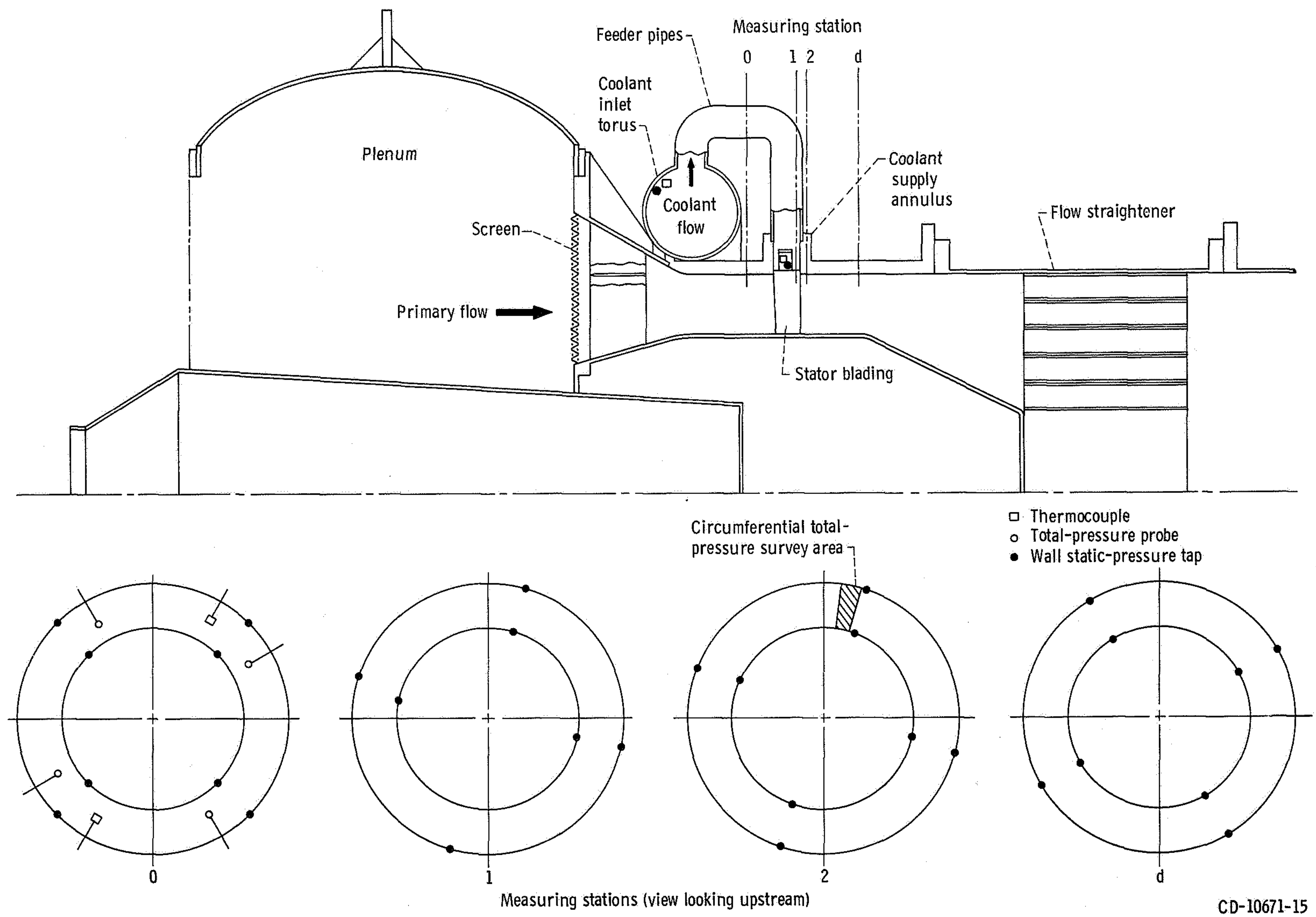


Figure 6. - Schematic diagram of turbine stator test facility and location of instrumentation.

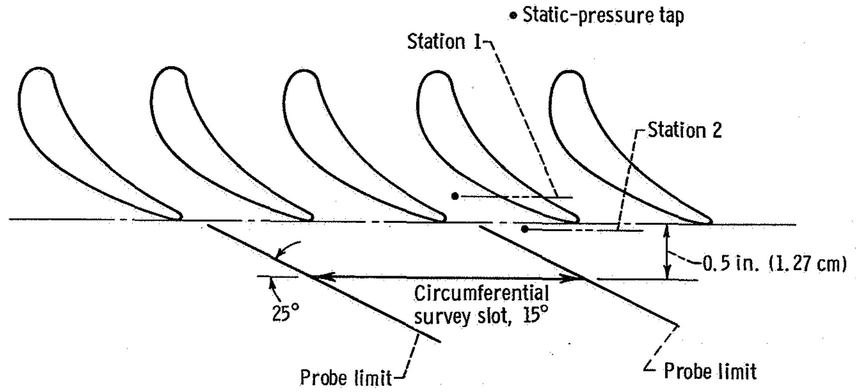


Figure 7. - Schematic of circumferential-total-pressure survey area, with approximate location of wall static-pressure taps.

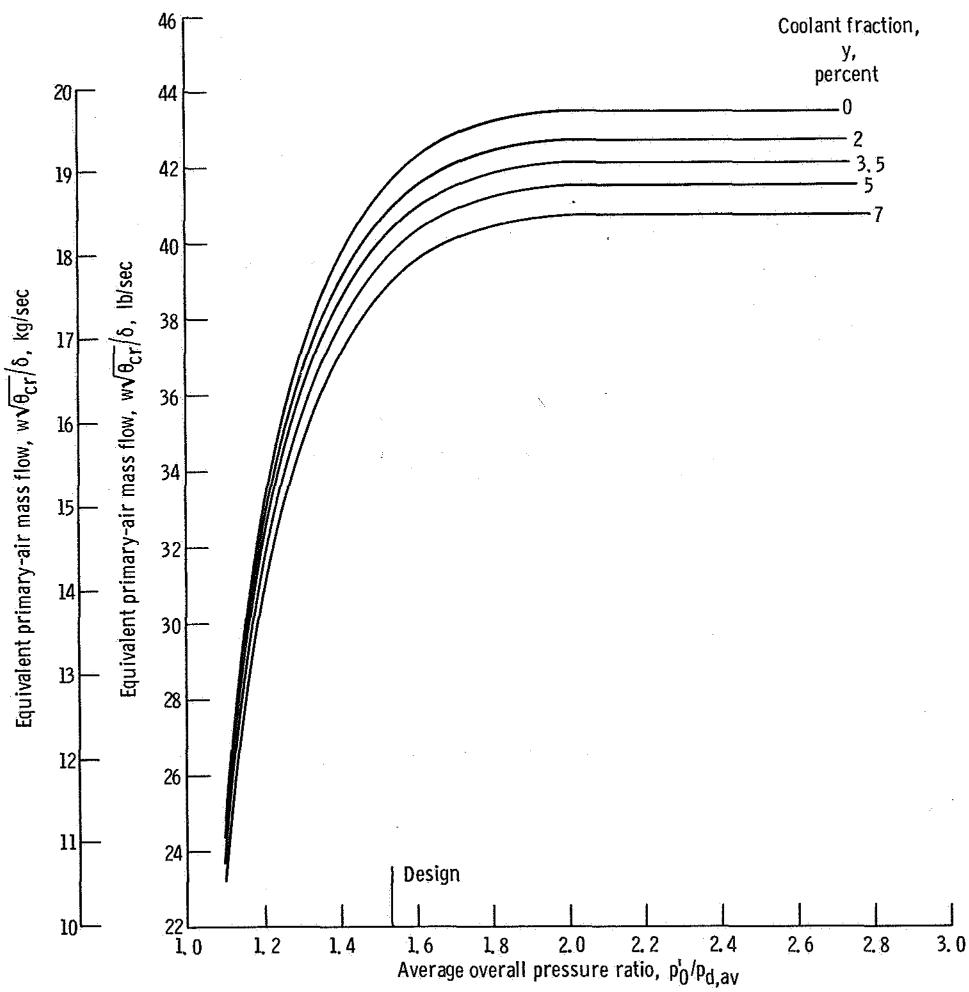


Figure 8. - Mass flow of stator with transpiration coolant.

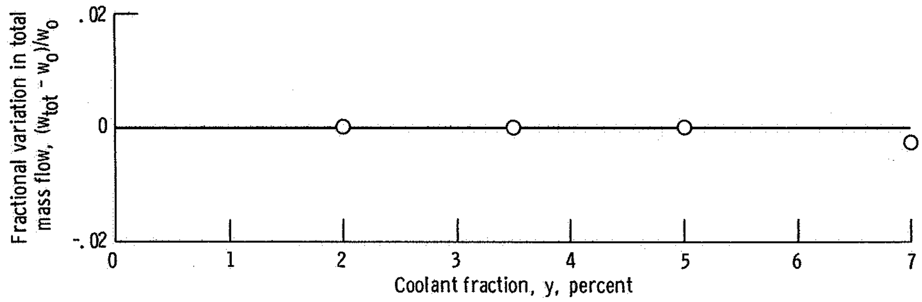


Figure 9. - Fractional variation in total mass flow as function of transpiration coolant flow rate.

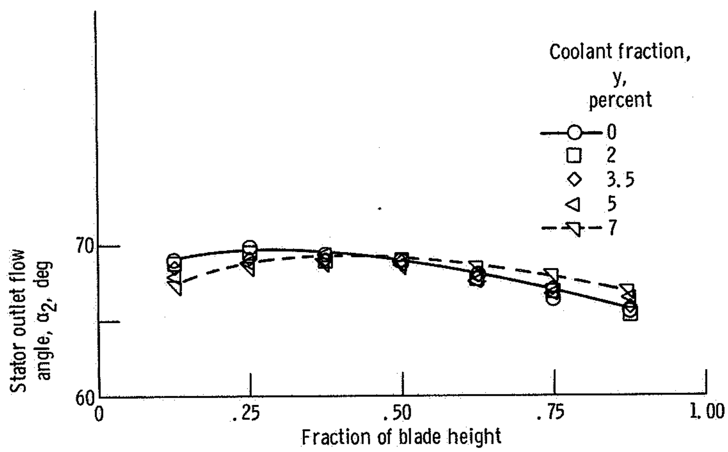


Figure 10. - Effect of coolant flow rate on stator free-stream outlet flow angle at design outlet hub pressure ratio.

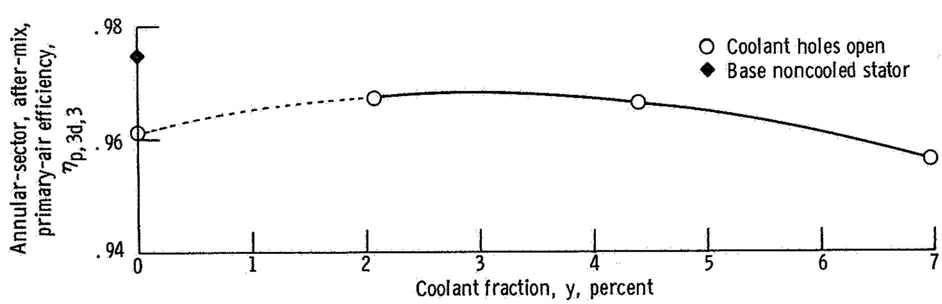


Figure 11. - Variation in stator primary-air efficiency with coolant flow rate.

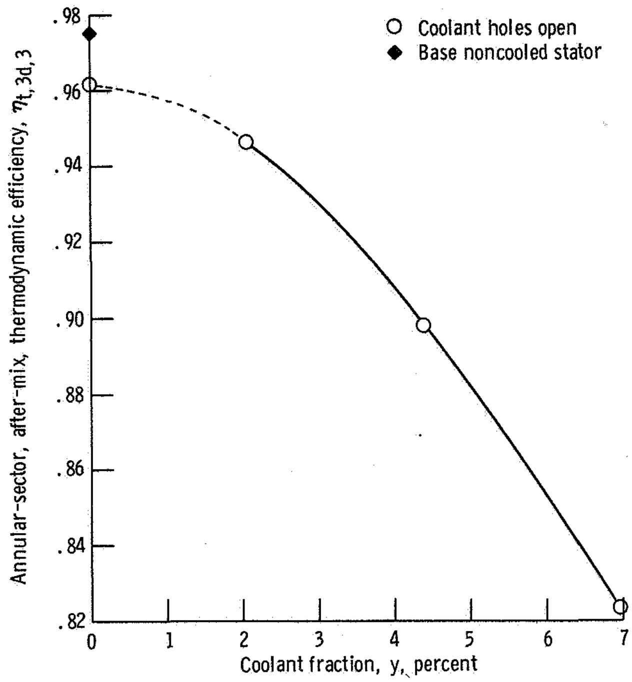
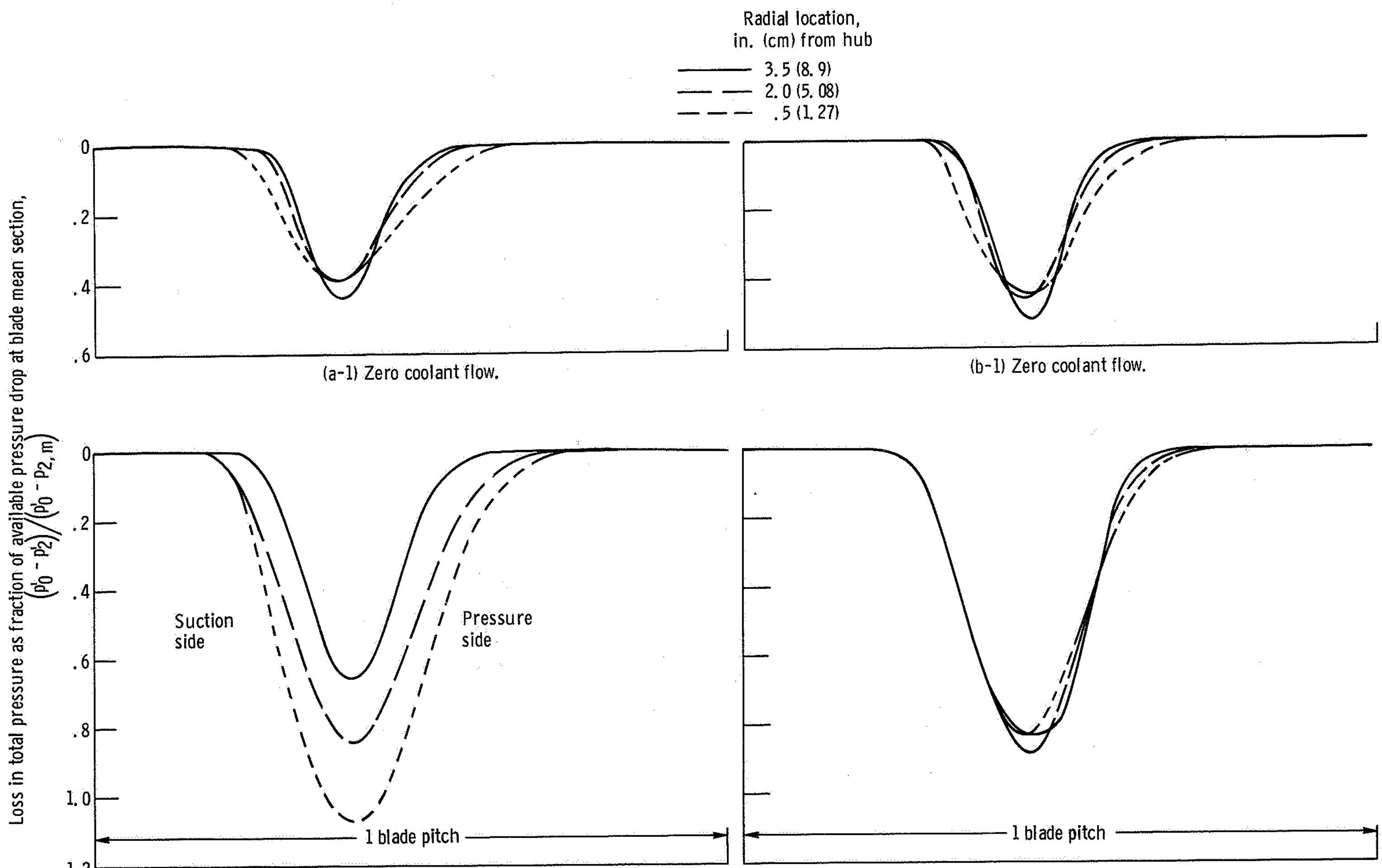


Figure 12. - Variation in stator thermodynamic efficiency with coolant flow rate.



(a-1) Zero coolant flow.

(a-2) Seven percent coolant flow.

(a) Wire-mesh shell blading.

(b-1) Zero coolant flow.

(b-2) Seven percent coolant flow.

(b) Discrete hole shell blading (ref. 5).

Figure 13. - Comparison of pressure-loss data for transpiration-cooled stator blades.

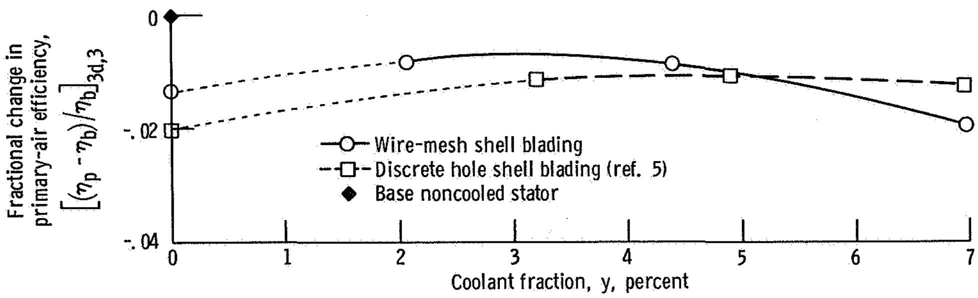


Figure 14. - Comparison of variation in stator primary-air efficiency for transpiration-cooled stator blades.

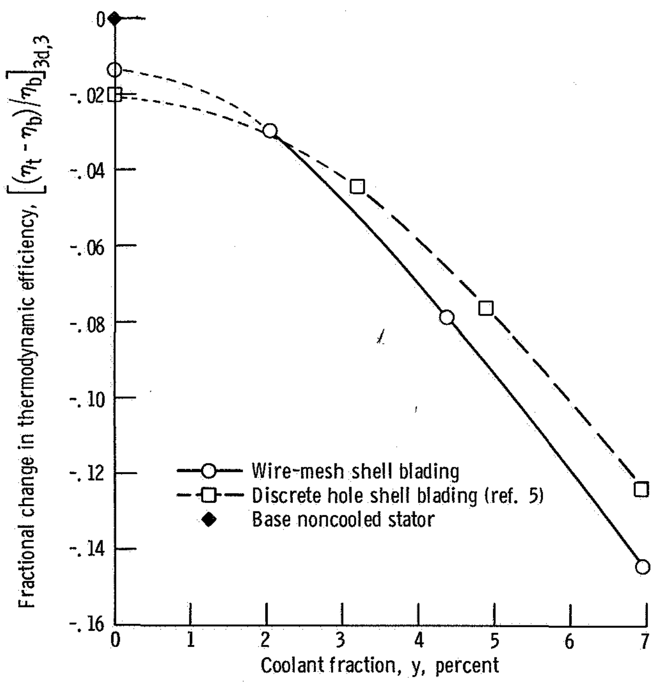


Figure 15. - Comparison of variation in stator thermodynamic efficiency for transpiration-cooled stator blades.

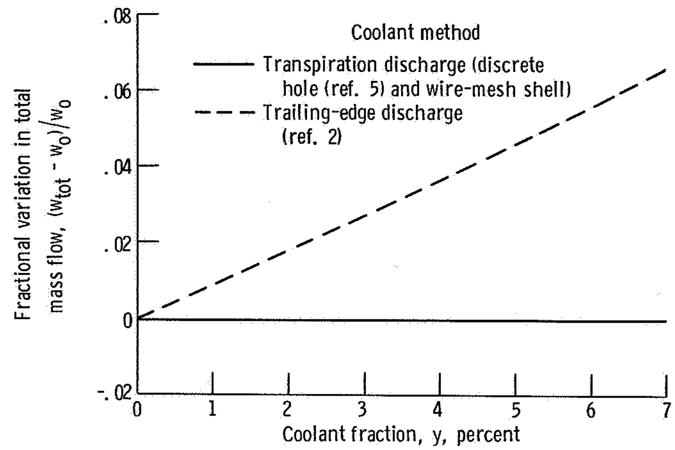


Figure 16. - Comparison of variation in mass flow for two types of transpiration coolant discharge and for trailing-edge coolant discharge.

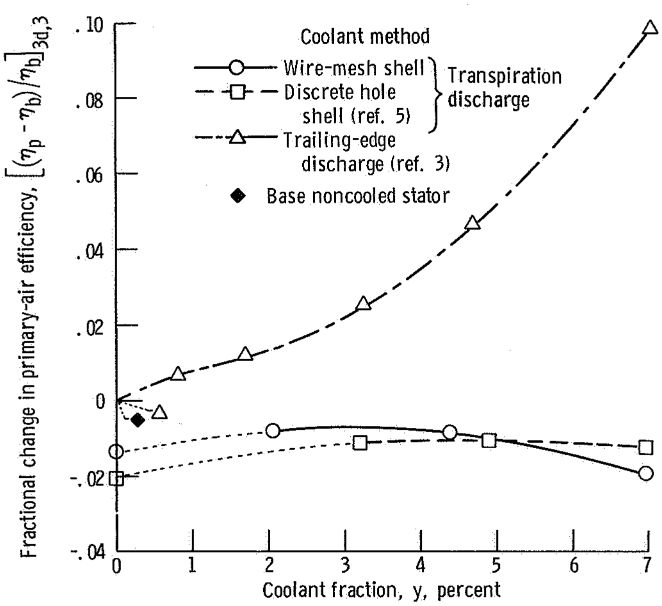


Figure 17. - Comparison of variation in stator primary-air efficiency for two types of transpiration coolant discharge and for trailing-edge coolant discharge.

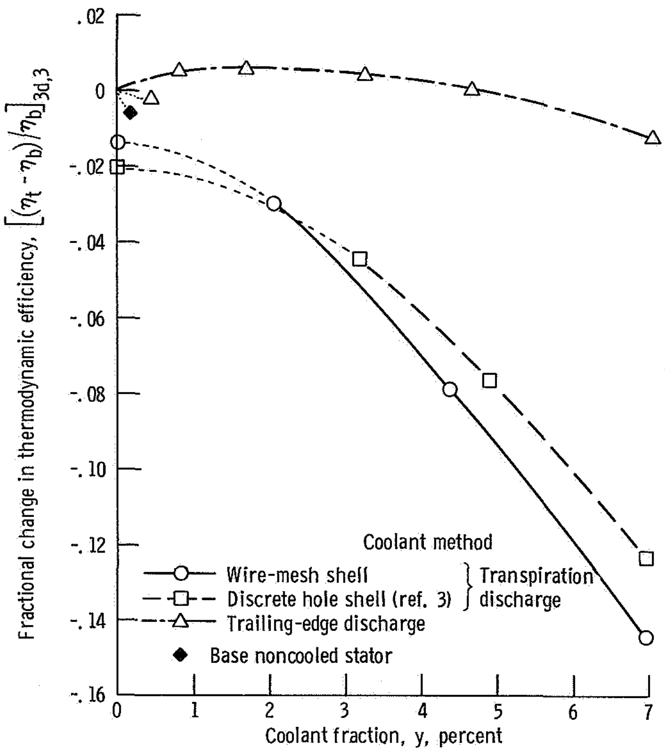


Figure 18. - Comparison of variation in stator thermodynamic efficiency for two types of transpiration coolant discharge and for trailing-edge coolant discharge.

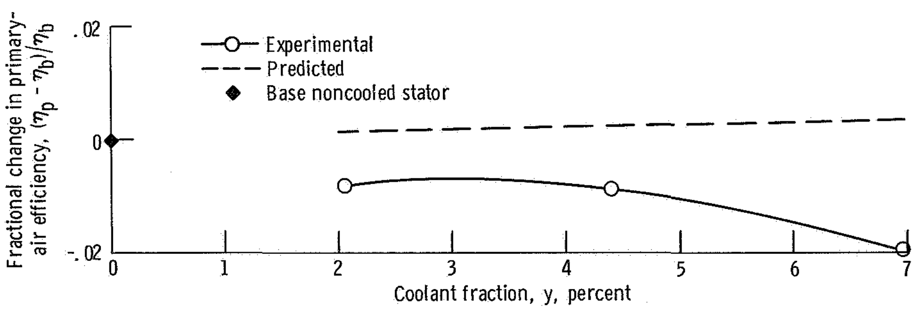


Figure 19. - Comparison of experimental and predicted changes in primary-air efficiency for wire-mesh shell blading.

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